# State of Nanomanufacturing & Overview of Day 3 Goals

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Center for High-rate Nanomanufacturing

MICHIGAN STATE UNIVERSITY

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UNIVERSITY of NEW HAMPSHIRE

# Focus on Current and Future Trends in Nanomanufacturing

## Goals of Day 3 Program

- The goal of the conference is to discuss research trends, needs and barriers in nanomanufacturing and articulate the community's vision for the future.

- Talks will provide background and set the stage for the discussion, talks will about 12 minutes to leave sufficient time for discussion

- Each panelists should address and state technical fundamental barriers as they see it based on their research as well as research conducted by others. These barriers will be collected in a report to enable this conference to articulate the fundamental barriers that need to addressed in future research projects.

# Focus on Current and Future Trends in Nanomanufacturing

## Summary of Day 3 Program

**9:00 Panel 8: New Concepts for Nanomanufacturing**

New and Novel concepts that could be used for nanomanufacturing

**10:30 Panel 9: Scalable Nanomanufacturing**

Scalability of newly developed nanomanufacturing processes

**12:20 Nanomanufacturing at NSF, Khershed Cooper, NSF**

**12:40 Innovation I-Corps Program Rathindra "Babu" DasGupta, NSF**

**1:00 Panel 10: Nano-enabled Integrated Systems**

Nano-enabled products and systems and role of Nanomanufacturing

**2:30 Panel 11: Advances in Modeling Nanomanufacturing Processes**

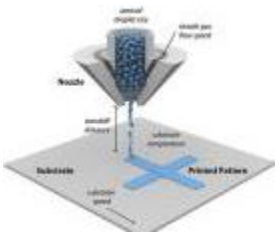
Addressing fundamental challenges in nanomanufacturing through modeling

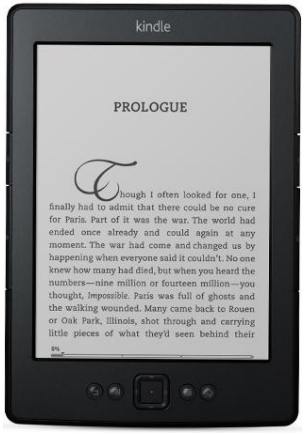
# What is the Current State of Nanomanufacturing?

- Considerable investment and progress have been made in nanotechnology, but integration of nanoscale materials and processes into products have been considerably slow.
- Commercial electronics device manufacturing is still mostly silicon-based, top-down and expensive, with factories costing billions and requiring massive quantities of water and power.
- Most current nanoscale devices do not as yet incorporate actual nanomaterials (nanotubes, quantum dots, nanoparticles, etc.) and thereby miss on the much-anticipated superior performance and unique properties.

# Current Use of Nanomaterials in Micromanufacturing

- Printing offers an excellent approach to making structures and devices using nanomaterials.
- Current electronics and 3D printing using inkjet technology, used for printing low-end electronics, flexible displays, cell phone RFIDs, are very slow (not scalable) and provide only micro-scale resolution.
- Screen printing is also used for electronics but only prints 100 microns or larger patterns.
- Even with these limitations, the cost of a printed sensor is 1/10th to 1/100th the cost of current silicon-based sensors.







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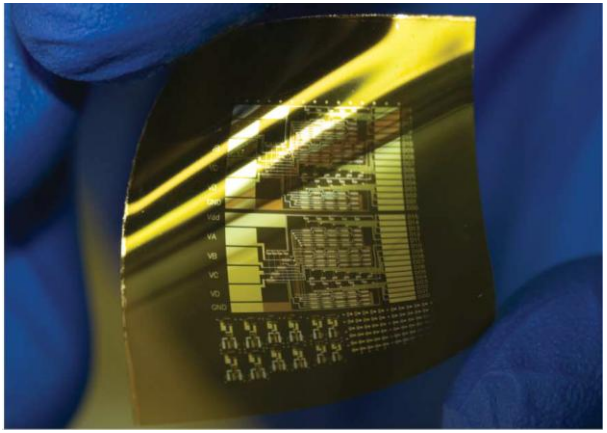
# Printed Electronics and Sensor

## Flexible Electronics



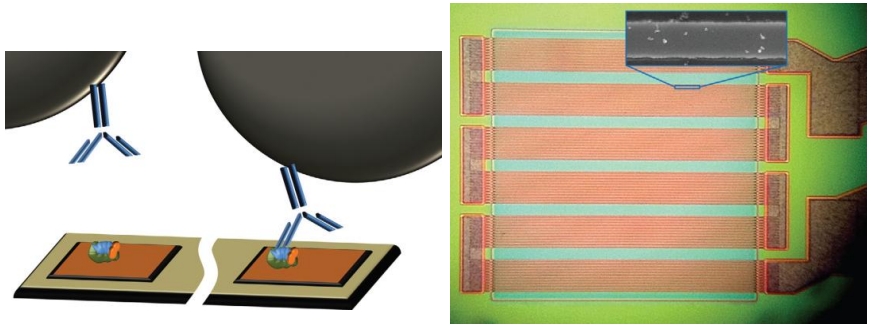
*Qing Cao et al., Nature, 2008*

## Flexible Display

*http://www.adzuna.co.uk/blog/2011/11/14/where-the-future-jobs-lie/460-cpi-printed-electronics/*

## Electronic Books

## Flexible biosensor using nanoparticle



*Richard S. Gaster et al., Nature Nanotech.,2011*

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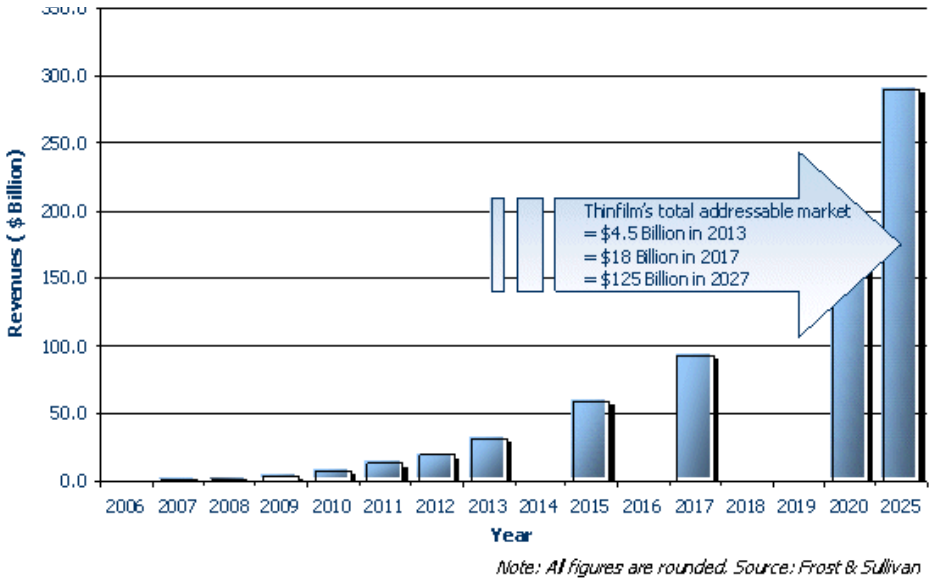
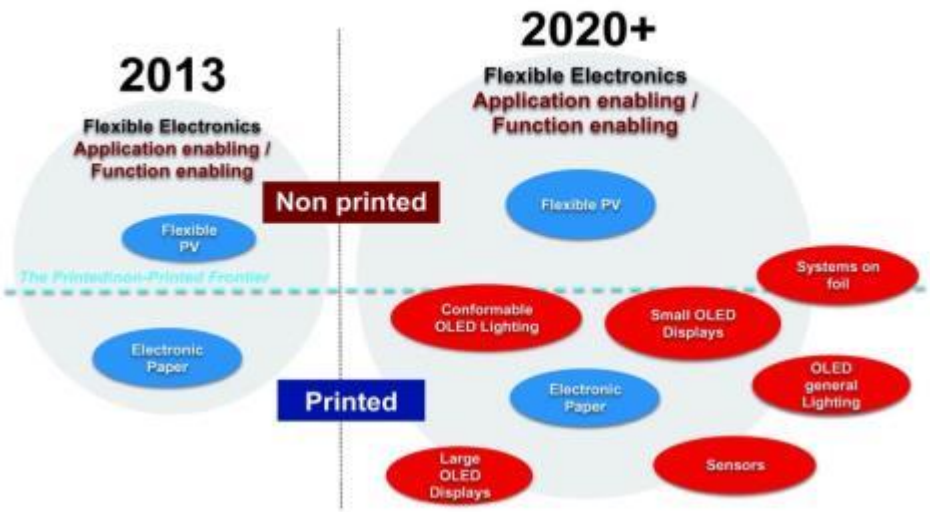
# Printed Electronics Market

## Printed Electronics - Market forecasts to 2025 - a $250+ billion market




*http://www.frost.com/prod/servlet/market-insight-print.pag?docid=108885683*

## Applications Landscape 2013-2020+




*Source: IDTechEx Organic & Printed Electronics Forecasts, Players & Opportunities 2007-2027*

- The end point for most applications is for the creation of disposable devices on low cost flexible substrates.
- The most difficult combination to achieve retaining yield, lifetime and manufacturing ease, but opening up the largest markets.

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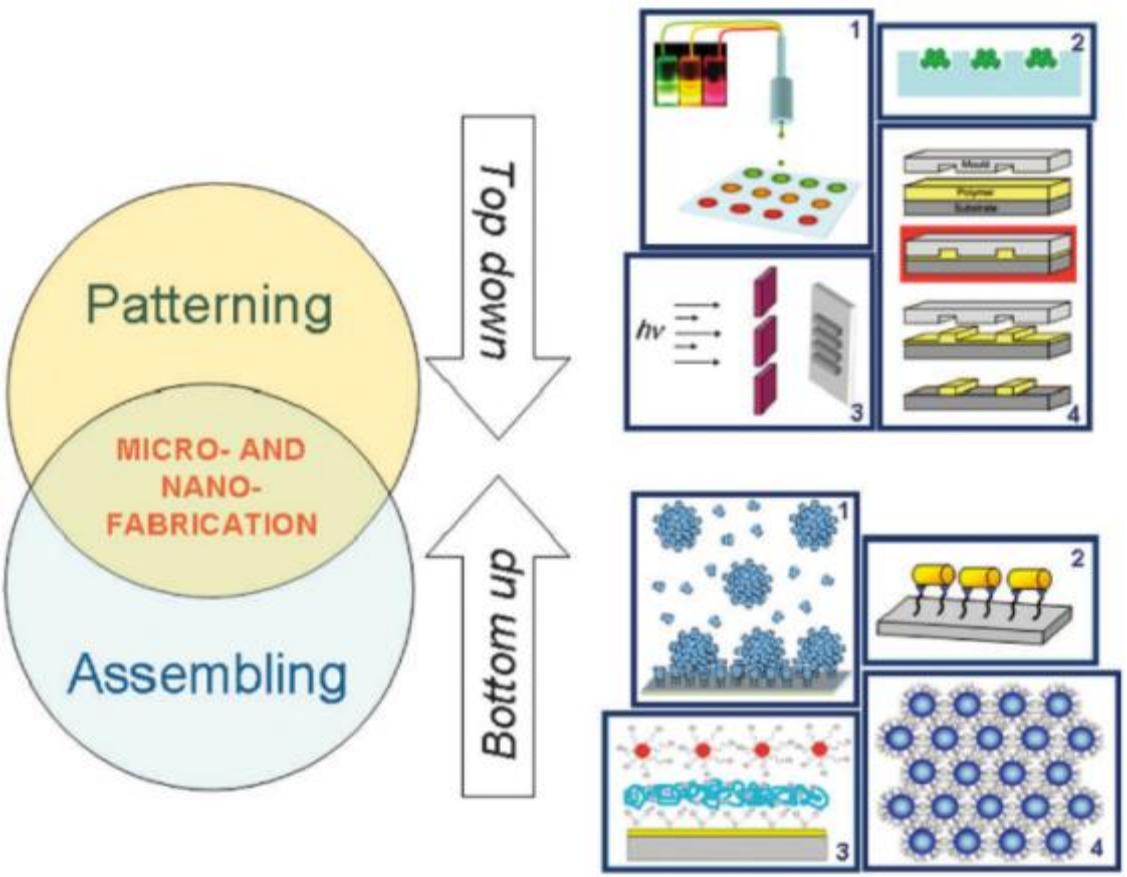
# Focus on Current and Future Trends in Nanomanufacturing

- For printed electronics and devices to compete with current silicon based nanoscale electronics, it has to print nanoscale features at:
  - orders of magnitudes faster than inkjet based printers and
  - at a small fraction of today's cost of manufacturing Si electronic.
- This will make nanomanufacturing accessible:
  - to millions of new innovators and entrepreneurs and
  - could produce a wave of creativity in the same way as the advent of the personal computer did for computing.

# Bottom-up/top down Nanomanufacturing Utilizing Directed Assembly

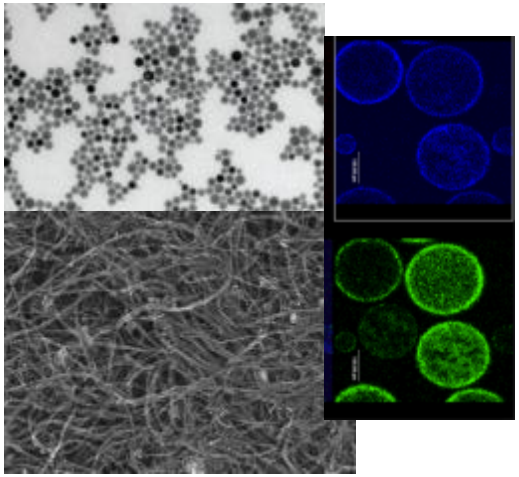



- **Top-down Fabrication techniques**
  - *Requires major facilities*
  - *Control below 30 nm is a challenge*
  - *Can not obtain high aspect ratio*
  - *Expensive process and facilities*
  - *Scalability to true nanoscale is still a question*

- **Bottom-up Synthesis**
  - *No standard 3D morphological control*
  - *Handling and alignment are difficult*

Directed Assembly based nanomanufacturing involves adding materials selectively.

# Directed Assembly

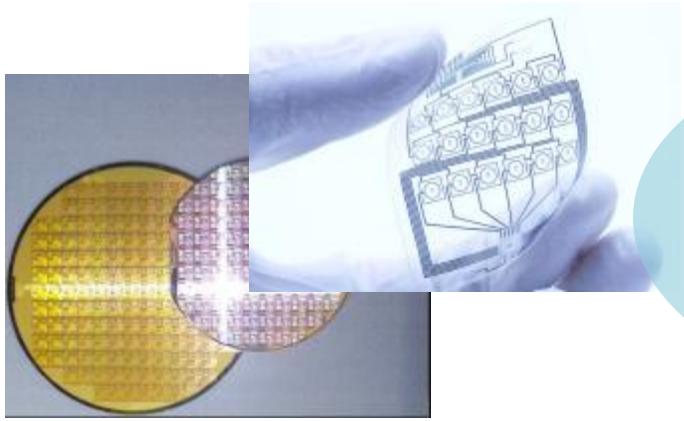


**NANOELEMENTS**

- Nanoparticles
- Nanotubes
- Nanowires
- Nanoflakes

**Directed Assembly**

- Electrostatic Forces
- van der Waals Forces
- Capillary Forces
- Electric Field
- Magnetic field



**TEMPLATES**

- Conductive-Insulating
- Flexible-Hard
- Patterned-Flat

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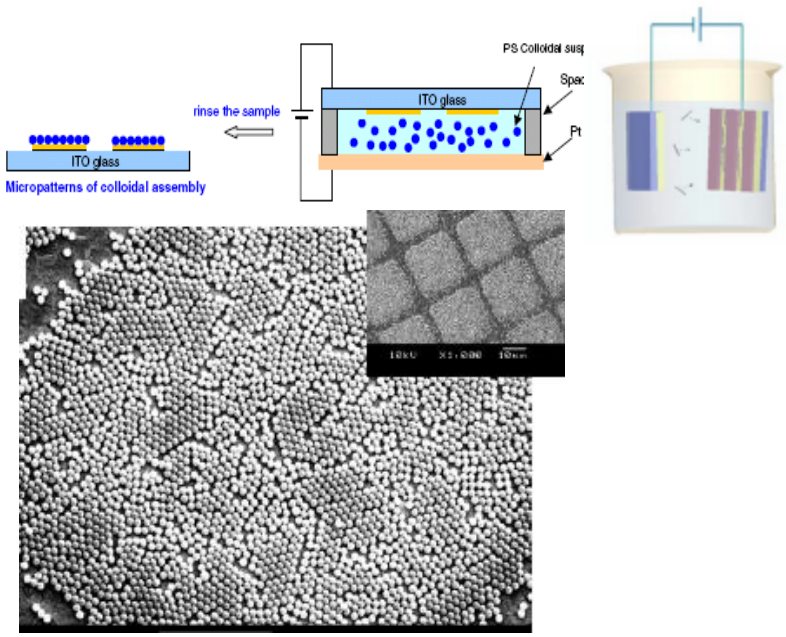
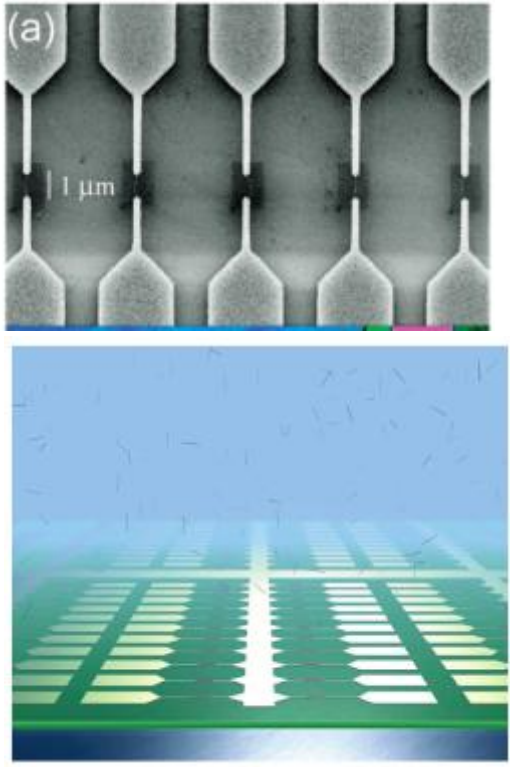
# Electric Field Directed Assembly

## Electrophoretic Directed Assembly




WM Choi et al. Nanotechnology, 2006, 17, 325–329

## Dielectrophoretic Directed Assembly




## Advantageous

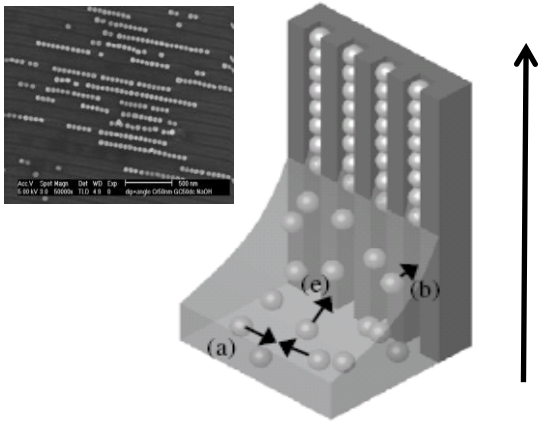
- Simple, fast
- Large scale

## Disadvantageous

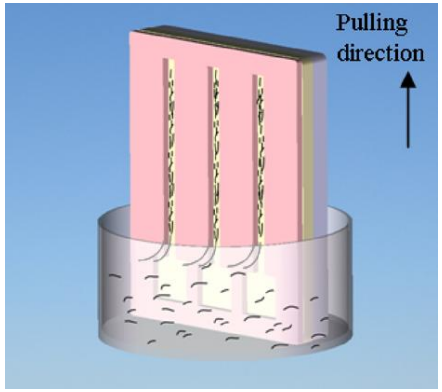
- Electrodes needed for assembly
- Assembly may result on a conductive surface

# Capillary Force Directed Assembly

## Template Guided Fluidic Assembly

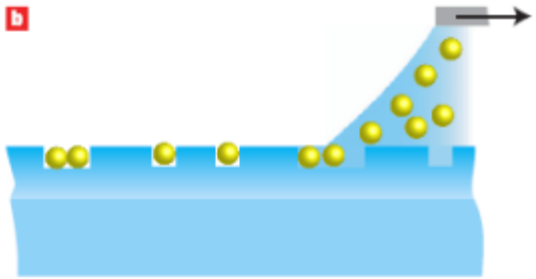



Juilerat F., et al. Nanotechnology 16 (2005) 1311-1316

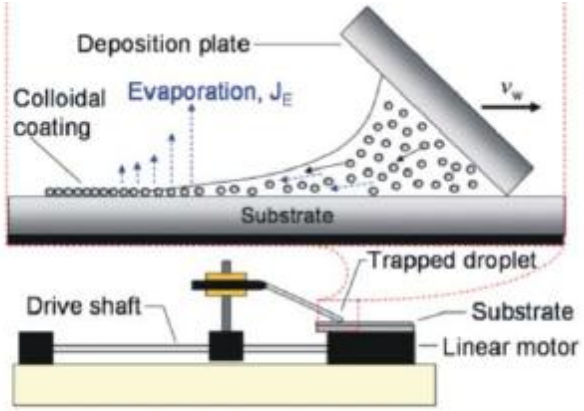



*X. Xiong et al., Small, 2007*

## Convective Assembly




*Tobias K., et al. Nature Nano, 2007*




### Advantageous

- Gives precise and good assembly
- Assembly on conductive or insulating substrates

### Disadvantageous

- Slow and not suitable for high rate manufacturing

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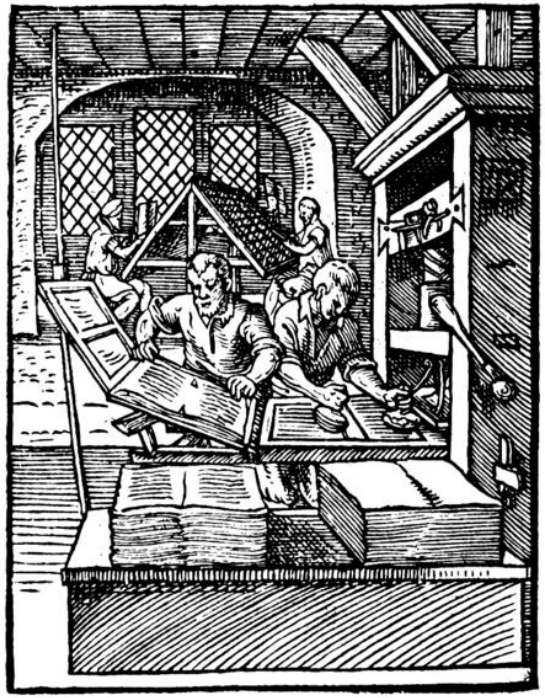
# Fabrication rate for different assembly techniques

| Assembly Method | Fabrication rate ($cm^2/h$) |
|---|---|
| Template Guided Fluidic Assembly | 10 |
| Surface Functionalization | 1 |
| Convective Assembly | 10 |
| Layer by Layer | 1 |
| Electrophoretic Deposition | 100 |

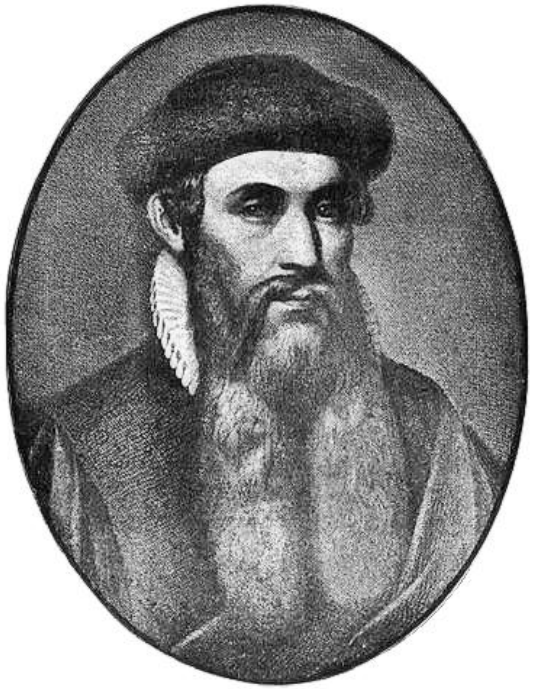
# A comparison between Different Approaches

| Assembly technique | Speed | Material of surface | External force | Scalability | Resolution |
|---|---|---|---|---|---|
| Fluidic | Very slow | C/NC | No | No | nm |
| Evaporation/convective | Very slow | C/NC | No | No | nm |
| Gravure | Fast | C/NC | Yes | Yes | >10 µm |
| LBL | Medium | C/NC | No | No | µm |
| Dielectrophoresis | Fast | C | Yes | No | nm |
| Electrophoresis | Fast | C | Yes | Yes | nm |

# How could we print at the nanoscale?



wooden printing press in1568., 240 prints per hour



Johannes Gutenberg, 1395-1468

Stanhope press from 1842


Modern Offset Printing

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# Introducing Nanoscale Offset Printing

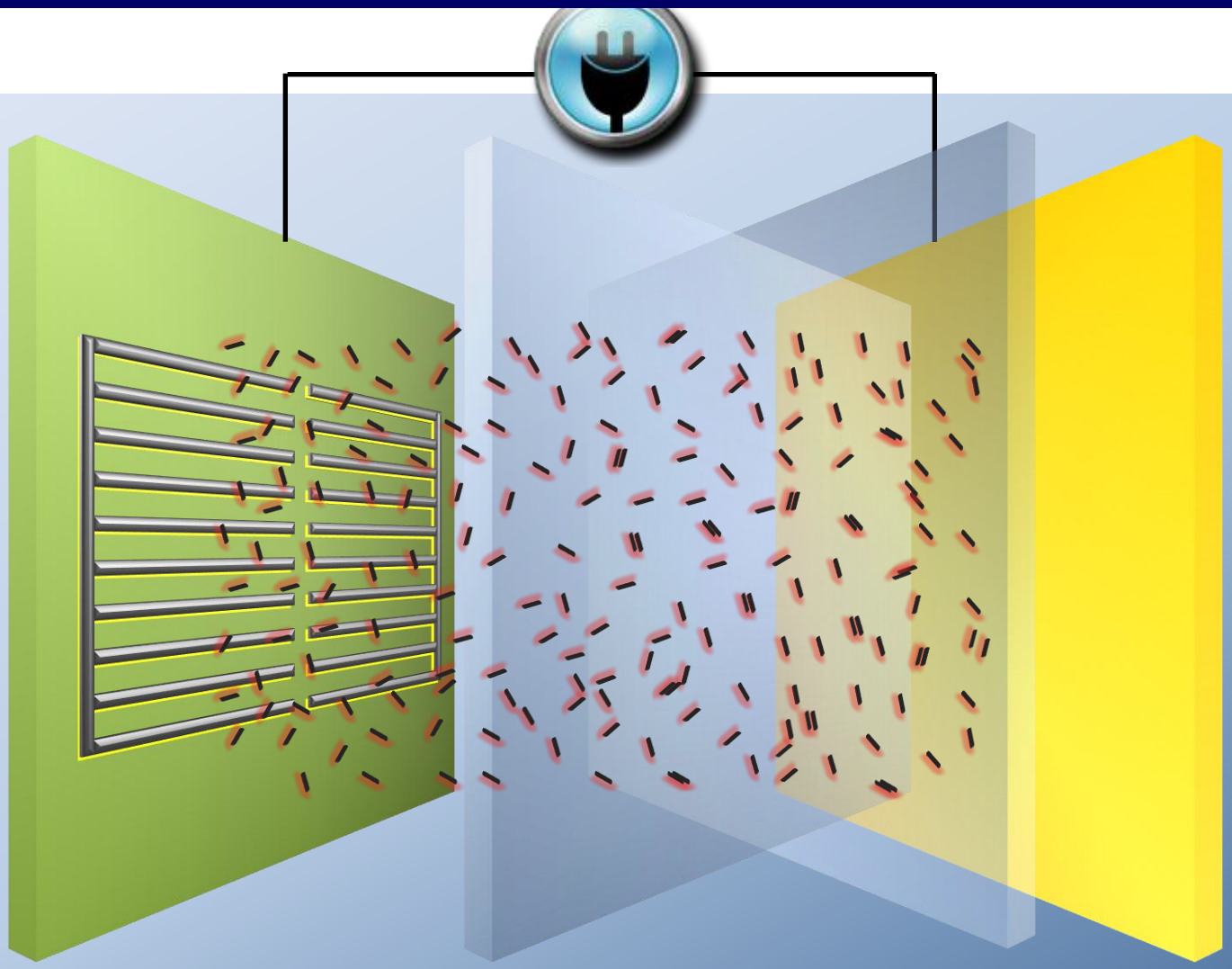
Nanoscale Offset Printing Template

Conventional Offset Printing

- Leveraging the directed assembly and transfer processes developed at the CHN, Nanoscale Offset Printing has been developed. The system is similar to conventional offset printing.
- The ink is made of nanoparticles, nanotubes, polymers or other nanoelements that are attracted to the printing template using directed assembly.
- This approach will be accomplished by integrating multiple directed assembly processes, printing and semiconductor manufacturing.

**This novel approach offers 1000 times faster printing with a 1000 times higher resolution.**

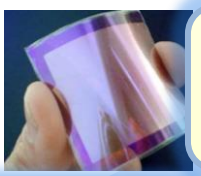
# How Does it Work?



# Beyond 3-D & Electronic Printing:
# Nanoscale Offset Printing Advantages

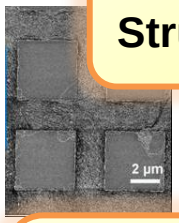
- Additive and parallel
- Scalable high throughput (much faster than 3-D printing)
- Printing down to 20nm
- Room temperature and pressure
- Prints on flexible or hard substrates
- Multi-scale; can print nano, micro and macro structures on the same layer
- Little use of chemicals (uses mostly water)
- Material independent
- Very low energy consumption
- Very low capital investment (equipment)

# What Could We manufacture with Multiscale Offset Printing?



CNTs for Energy Harvesting

Assembly of CNTs and NPs for Batteries




2-D Assembly of Structural Apps.

Antennas, EMI Shielding, Radar, Metamaterials

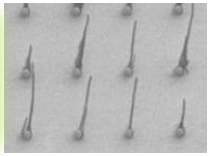
Materials

Energy

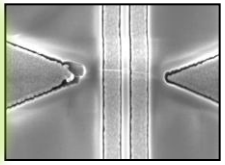
Electronics

Flexible Electronics

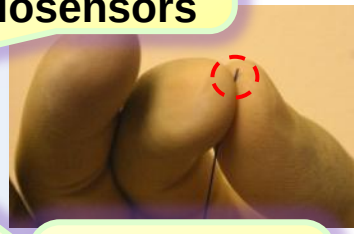
SWNT & NP Interconnects



SWNT NEMS & MoS2 devices

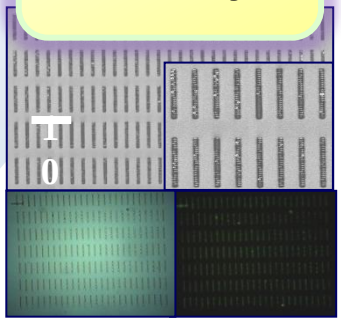


Multi-biomarker Biosensors



Bio/Med

Drug Delivery



Directed Assembly and Transfer

Nanoscale Science

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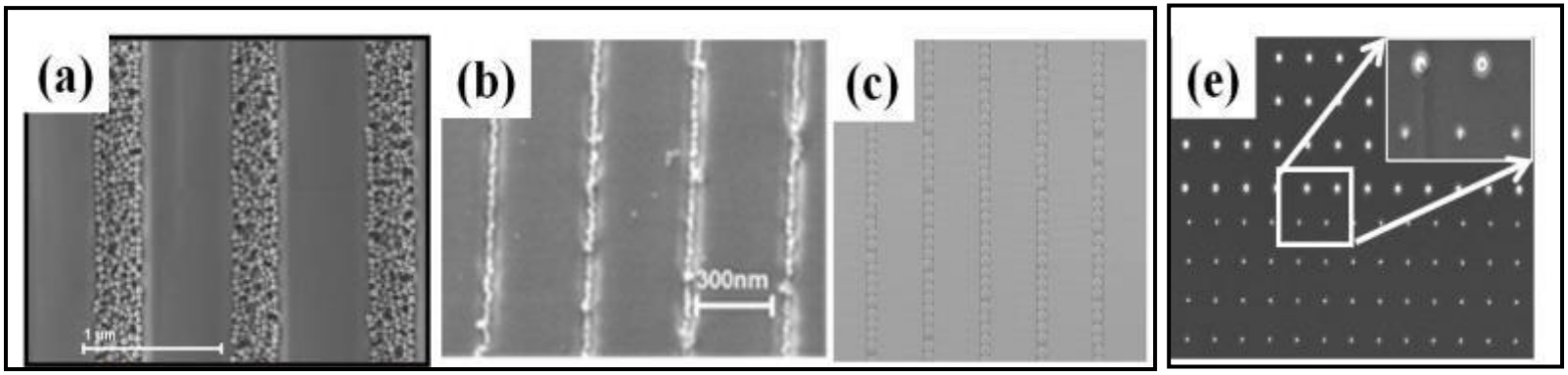
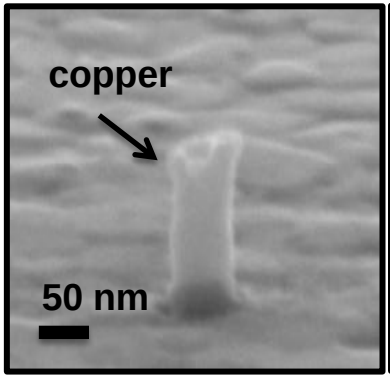
# Nanomaterials-based Manufacturing

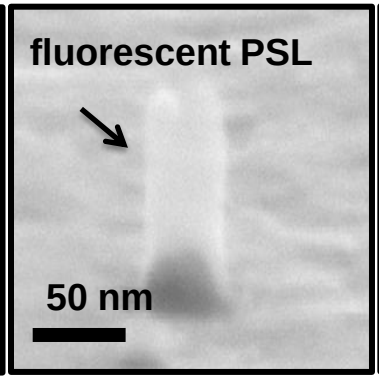
## Nanoscale Offset Printing

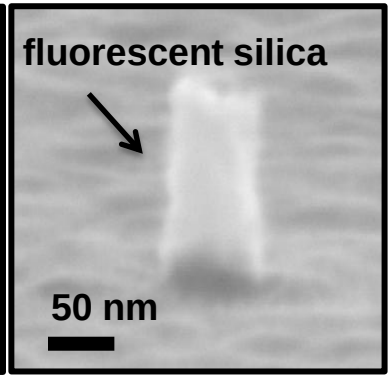
# Printing of Nanoparticles

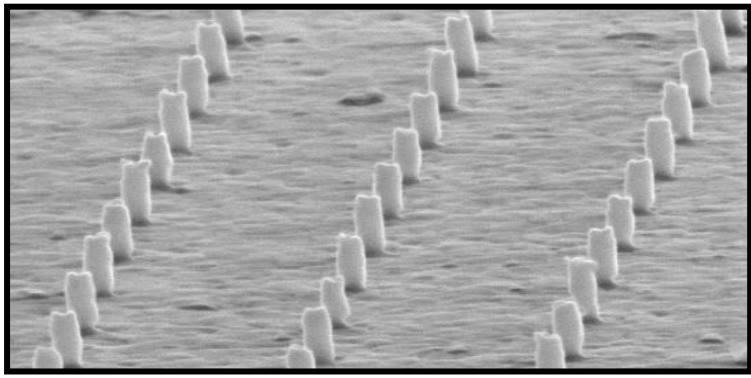
2D Assembly

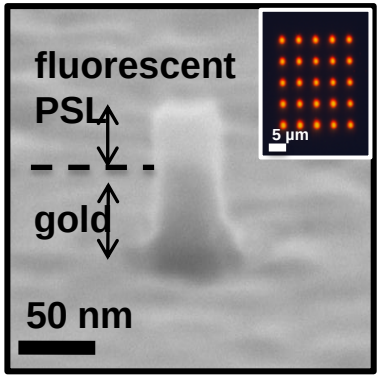


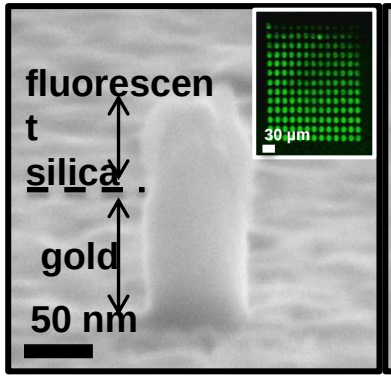



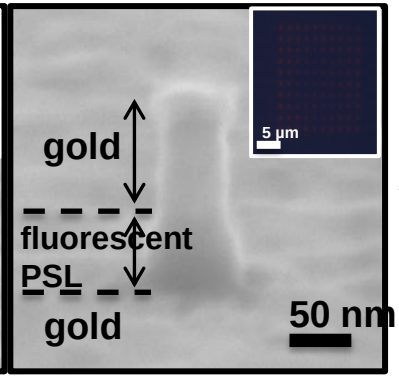



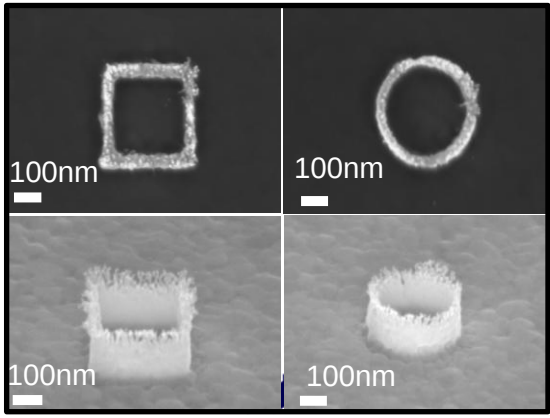





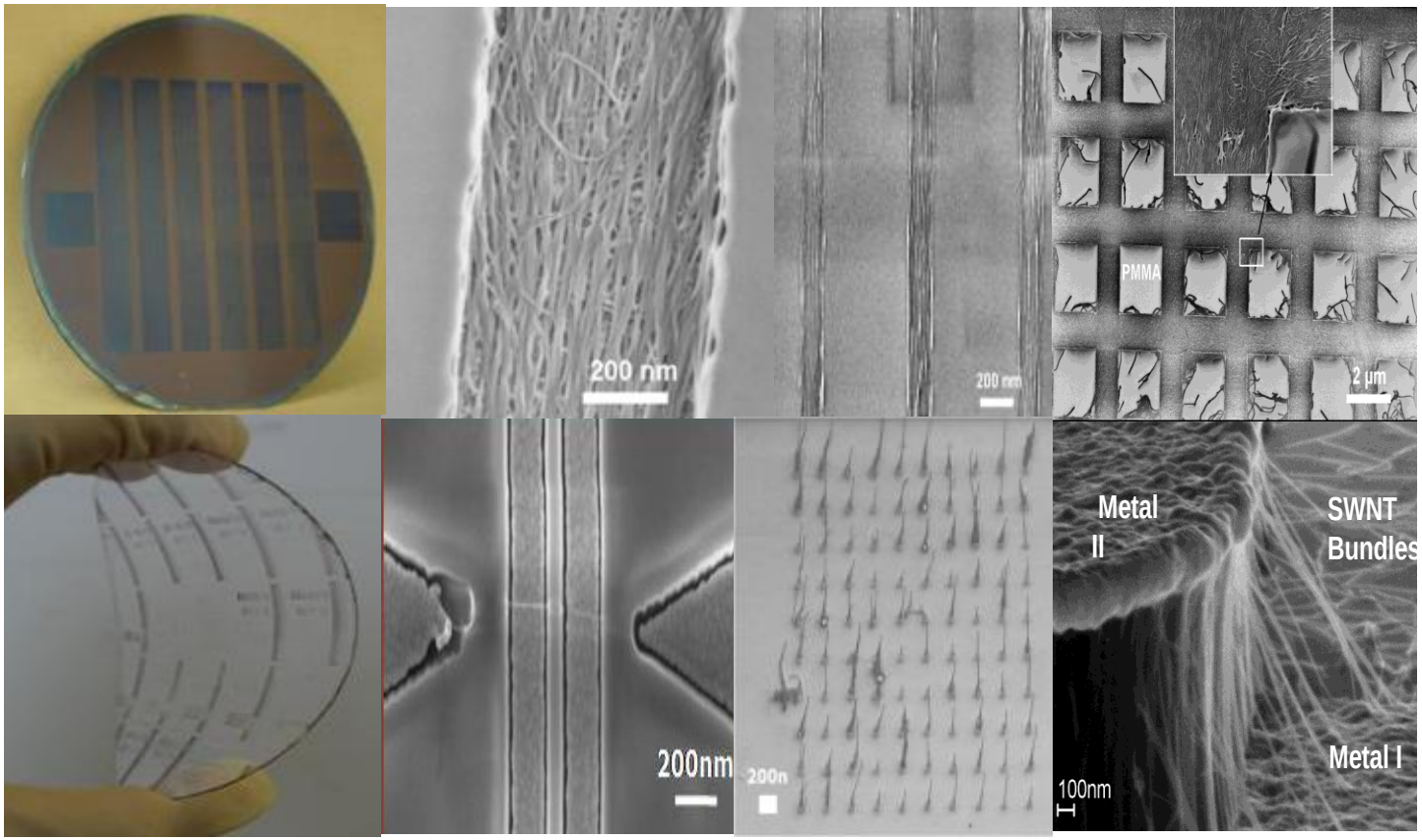



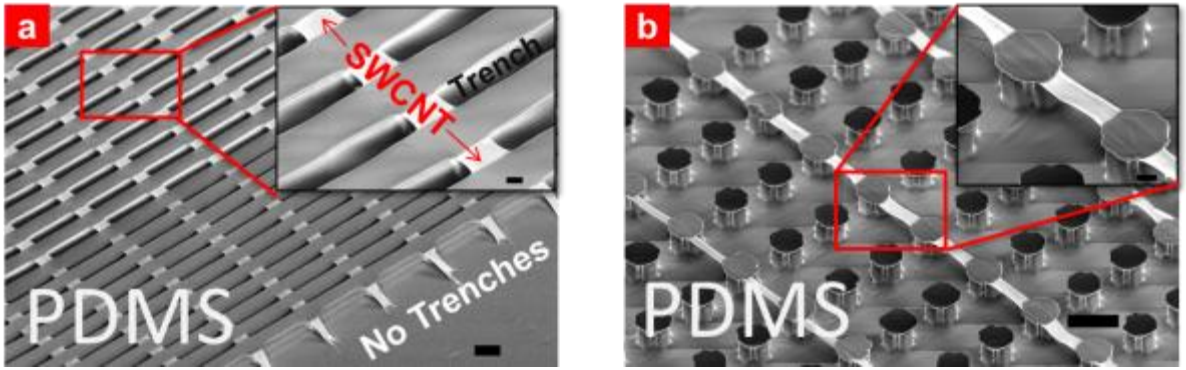

3D Assembly



# Printing of Carbon Nanotubes

2D Assembly




3D Assembly

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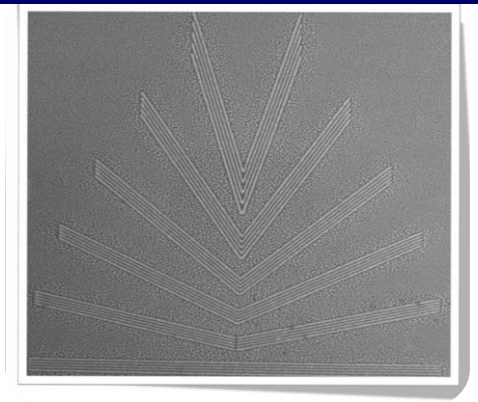
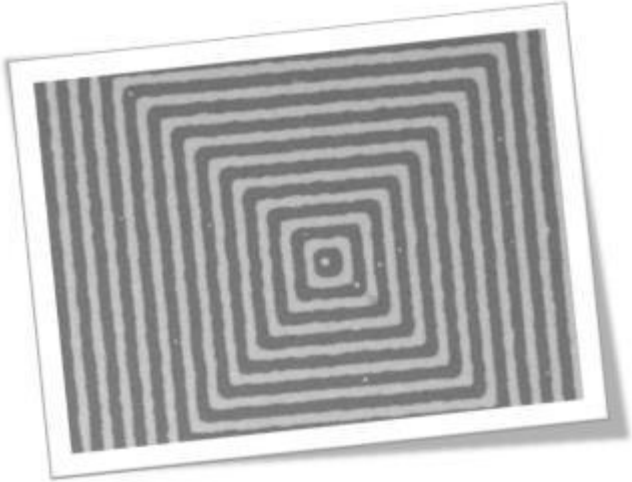
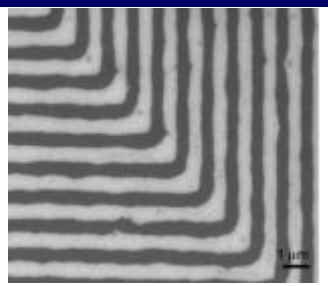
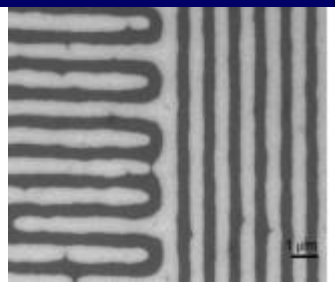
# Printing of Heterogeneous Polymers



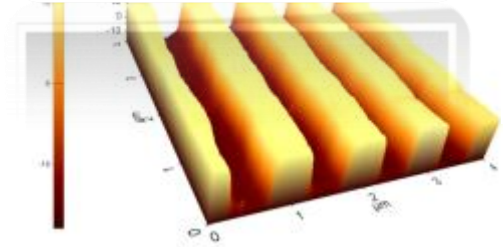




90˚ bends

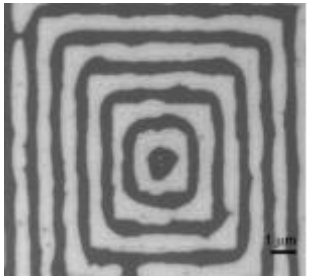


T-junctions

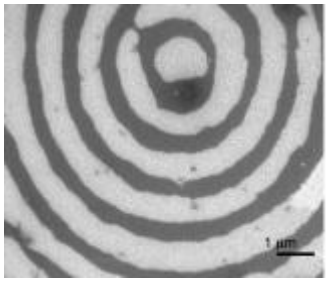


3D Assembly

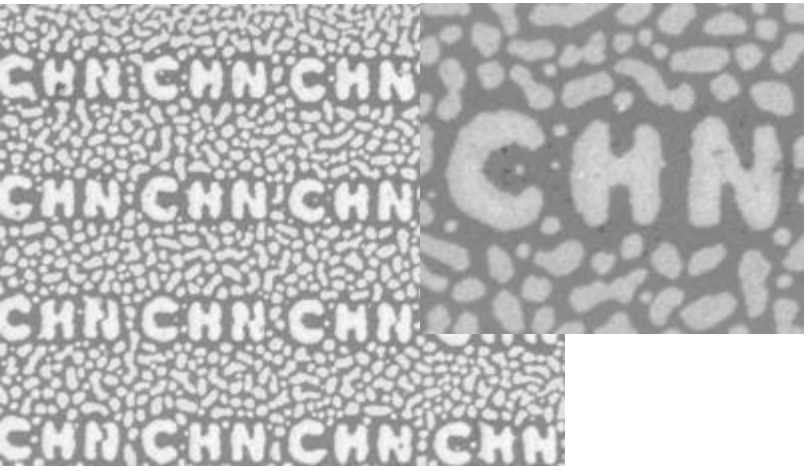
**Multiple polymer systems,**
**Rapid Assembly, multi-scales**

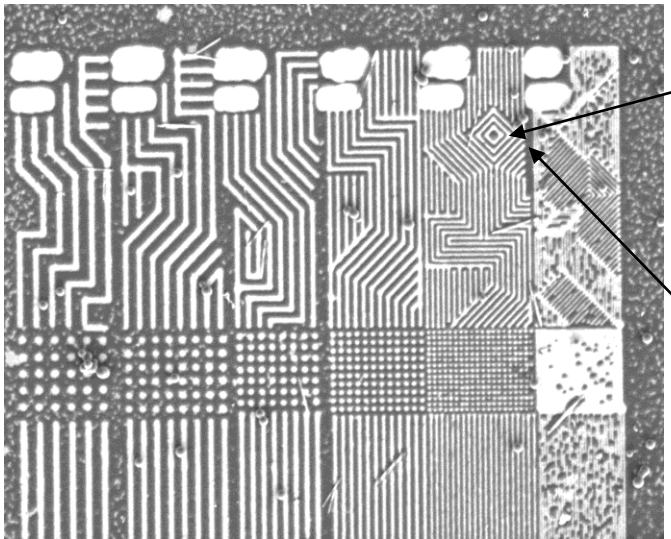


Square arrays



Circle arrays




2D Assembly

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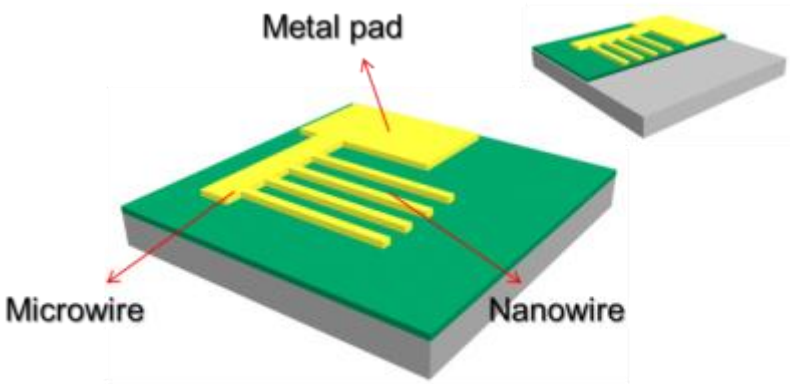
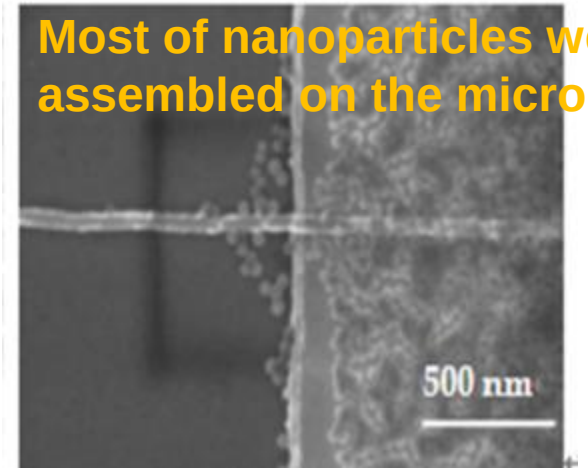
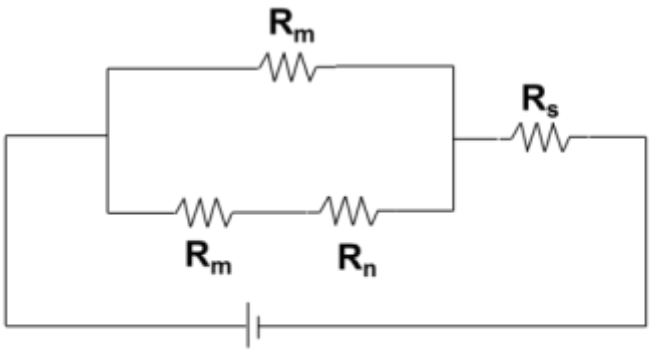
# Micro/nanowire Template

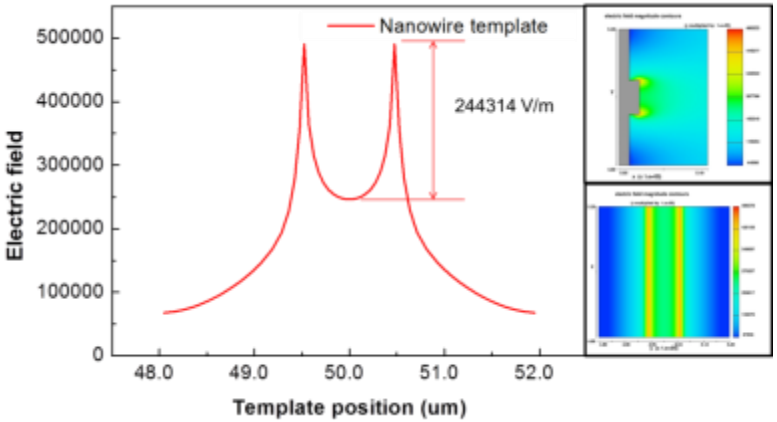



$R_m << R_n << R_s$

**Non uniform electric field across the wire**




- Potential drop along the nanowire.
- Non-uniform assembly results.
- Peeling off from the substrate due to the poor adhesion.

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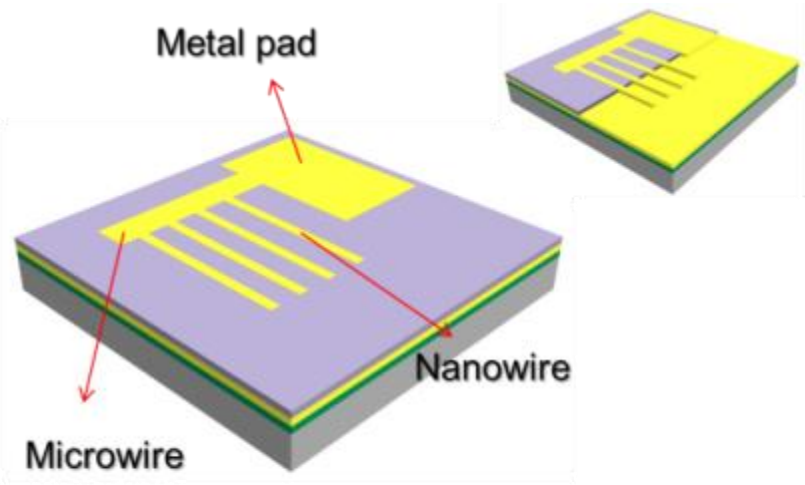
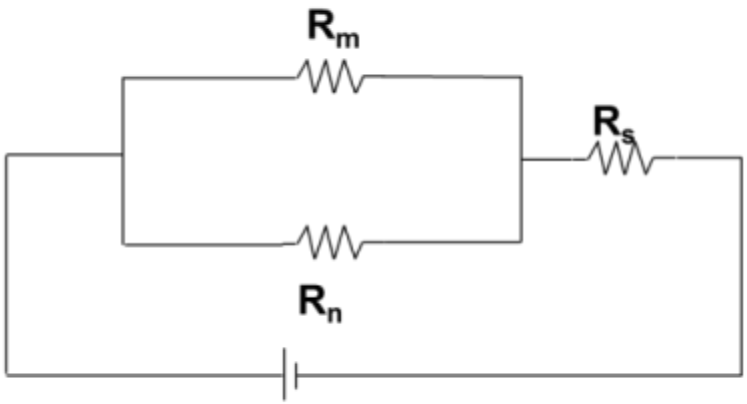
# Damascene Template



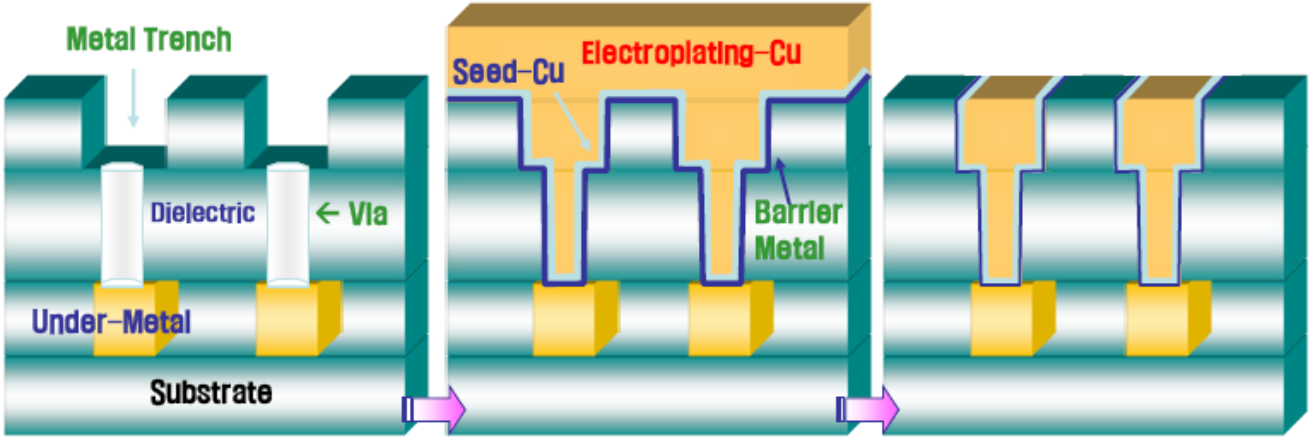

$R_m \sim R_n << R_s$

- **All features are connected to the conductive film** underneath the insulating layer.
- **Uniform electric field** on all nano/micro features.
- **Strong adhesion force** between the conductive patterns and substrate.
- **No indentation mark** on the flexible substrate after transfer process.
- **The template can be reused** in the cycle without any additional process.

# What is Damascene?

## Damascene structures

- Originates from Damascus, from the 3rd to 17th century
- For multilayer of two different steel and decoration of sword surface using gold.




SEM view of Copper Interconnect
(IBM Microelectronics)

- **IBM invented copper damascene process for interconnect in 1998.**
- **Semiconductor industries use damascene structure for copper interconnect on all electronics we use today.**

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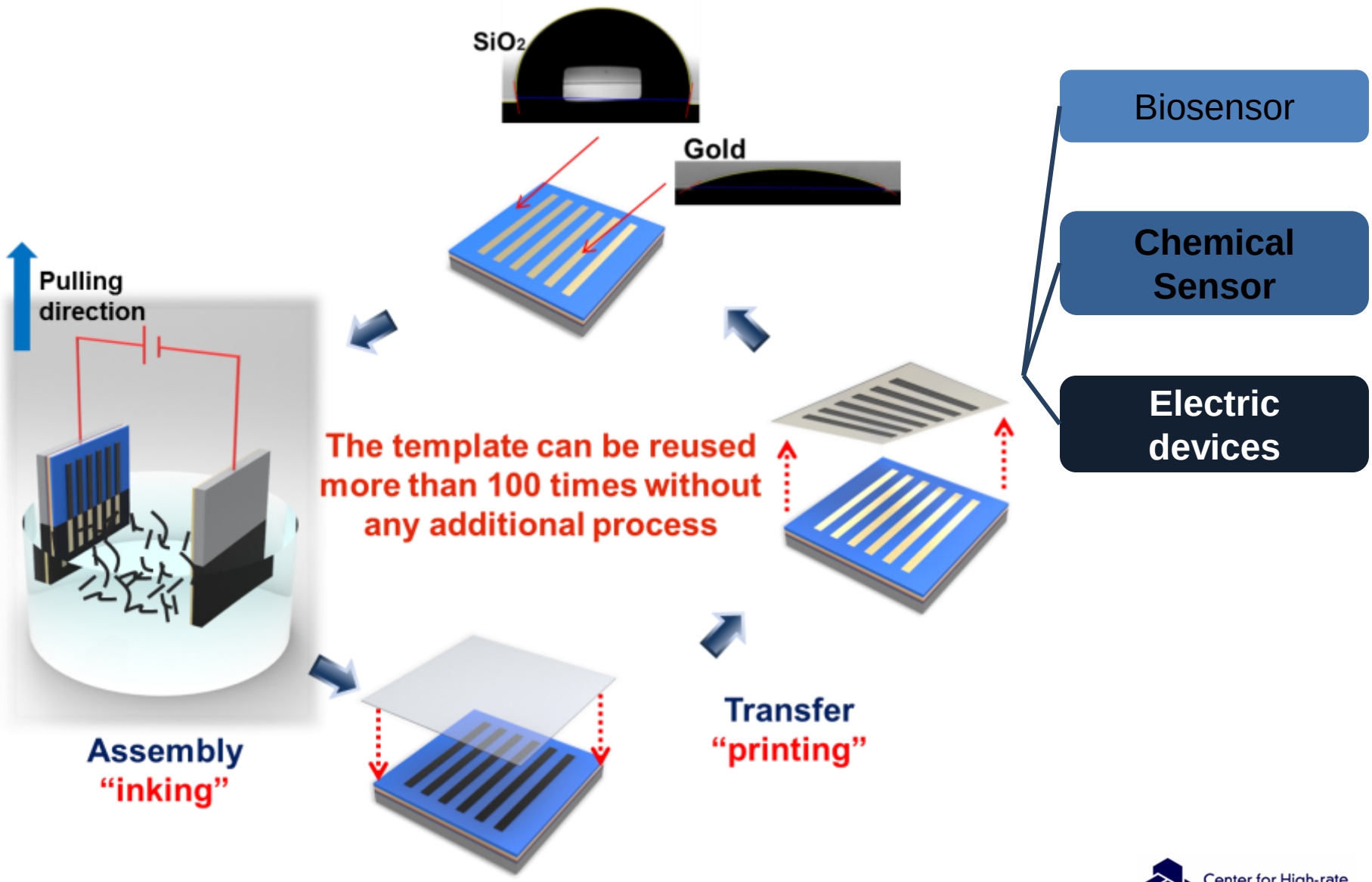
# Offset Printing Procedure

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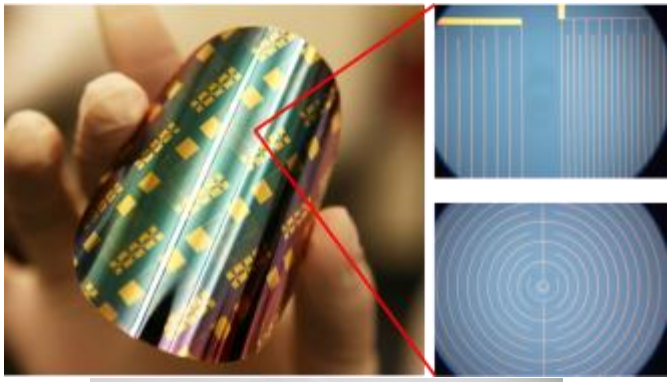
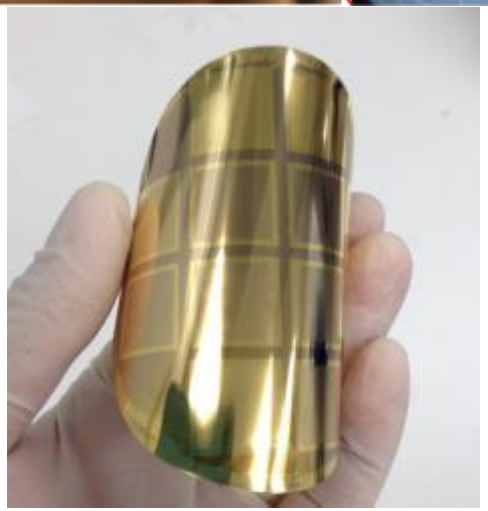
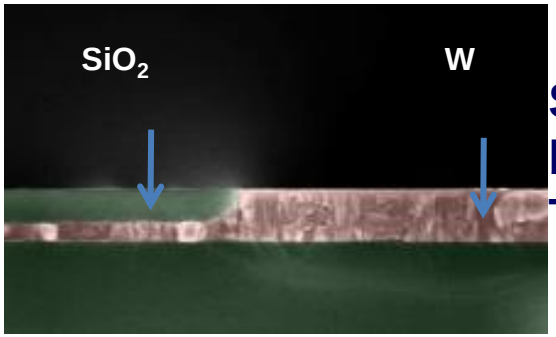
# Damascene Templates for Nanoscale Offset Printing

PEN

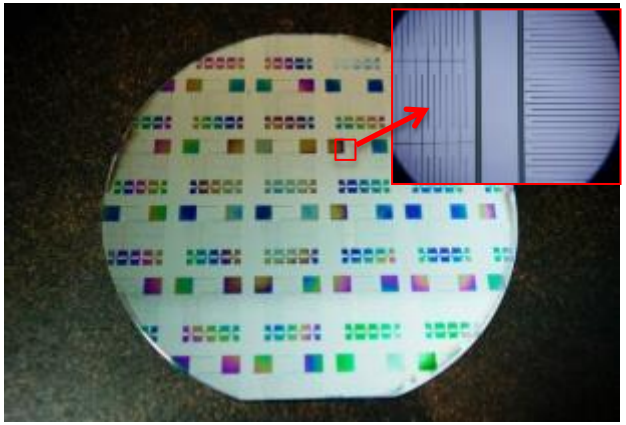


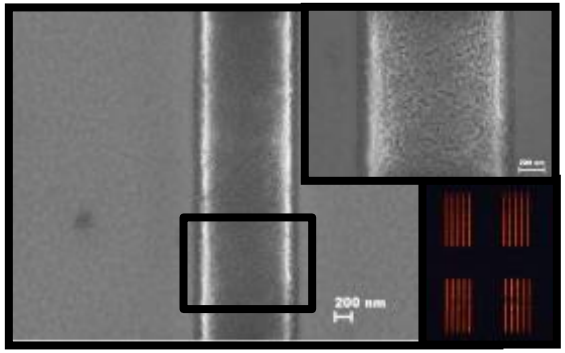
PI

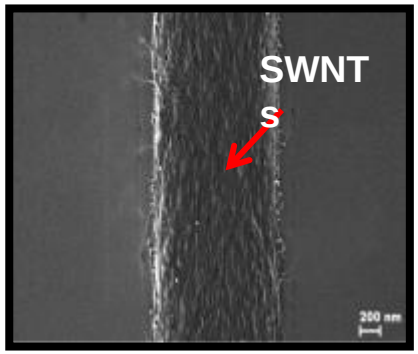


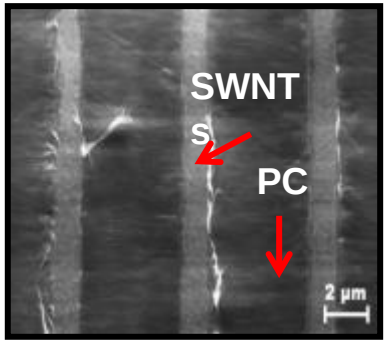


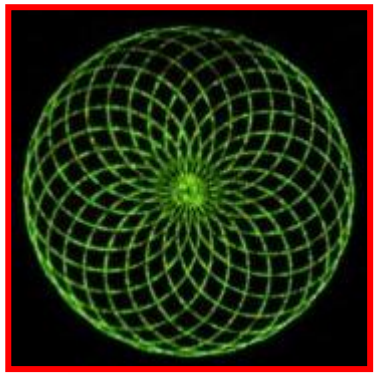

**Silicon-based Hard Templates**





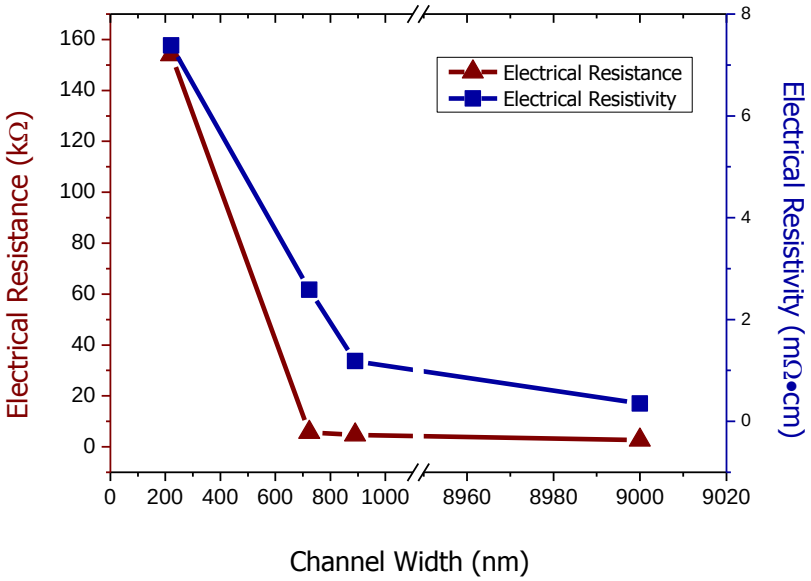



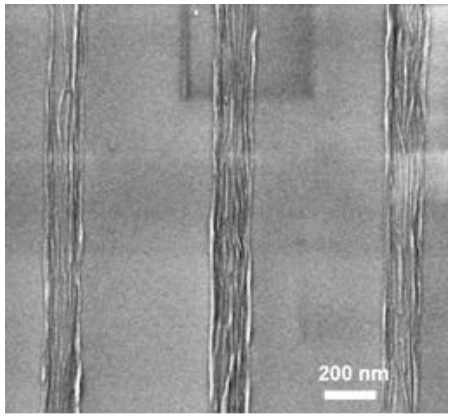



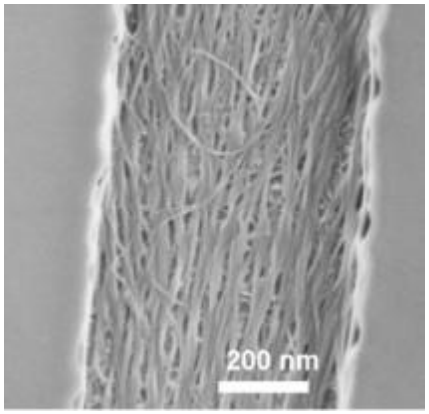



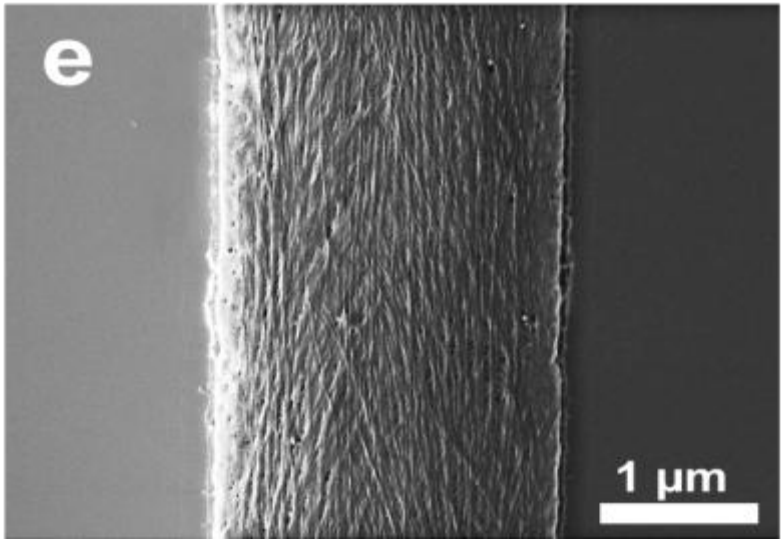
# Electrical Properties of Printed Aligned SWCNT Networks

## Two-terminal I-V Properties




- Alignment gives the network semiconducting behavior

Somu, Jung, Busnaina, et. al., ***ACS Nano, 4, 4142-4148 (2010)***

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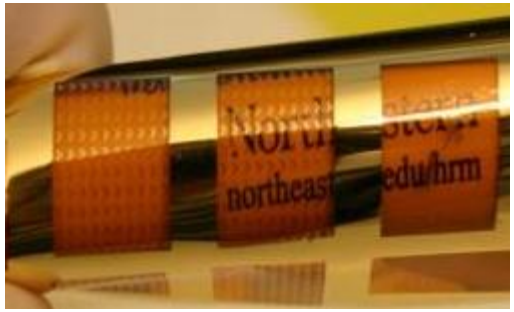
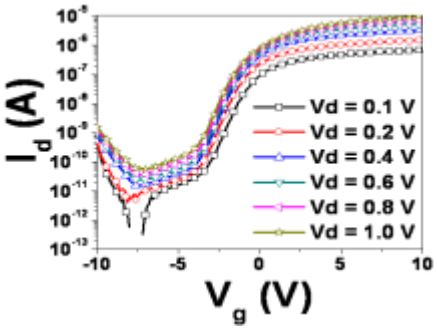
# Electronics

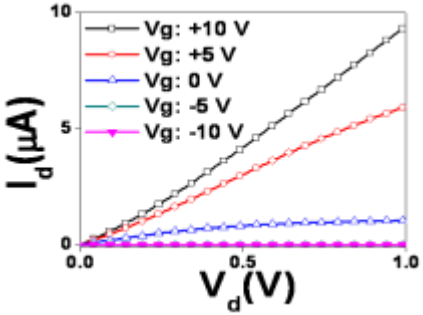
# Electronics

- **Flexible transparent n-type $MoS_2$ transistors**

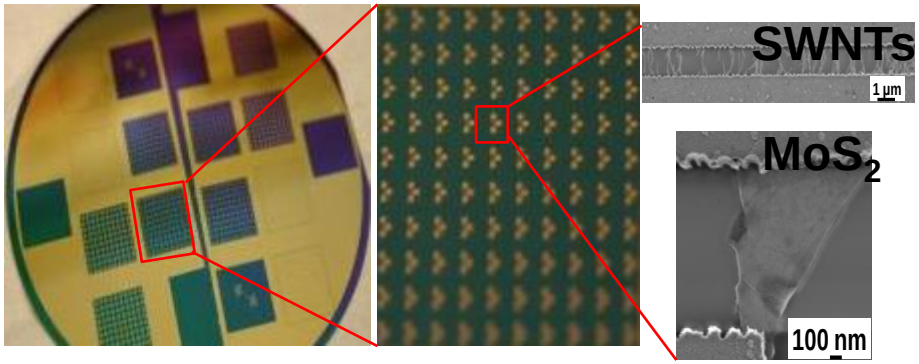
*Nanotechnology, Vol. 22, (2011)*

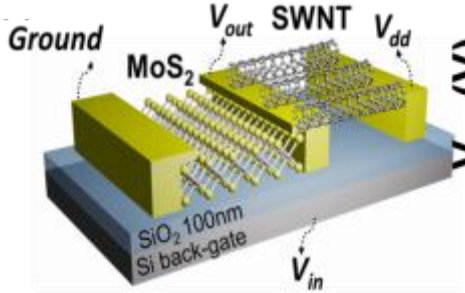


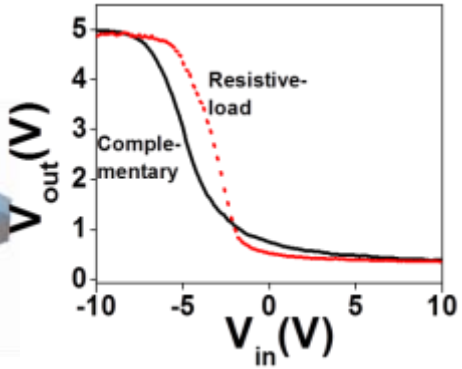



- **Heterogeneous SWNTs and $MoS_2$ complimentary invertors through assembly**



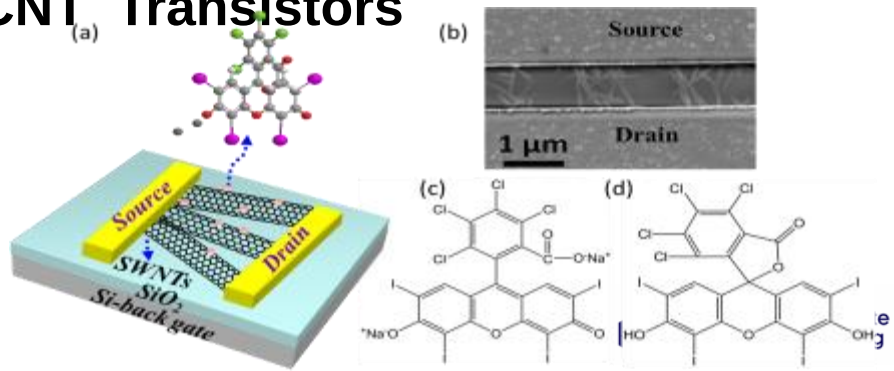




*Nanotechnology, Vol. 23, (2012).*

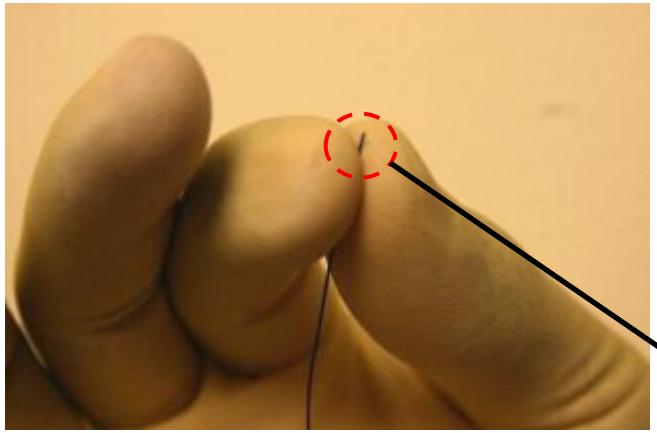
- **Rose Bengal Molecular Doping of CNT Transistors**

  - RB-Na doping shifts the threshold voltage of CNTFETs up to ~6V, lower the sub-threshold swing for 4 times, and increase the effective field-effect mobility



# Sensors

# In vivo Nano Biosensor



- ✓ Multiple-biomarker detection
- ✓ High sensitivity
- ✓ Low cost
- ✓ Low sample volume
- ✓ In-vitro and In-vivo testing

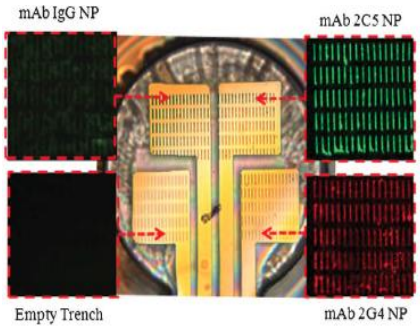
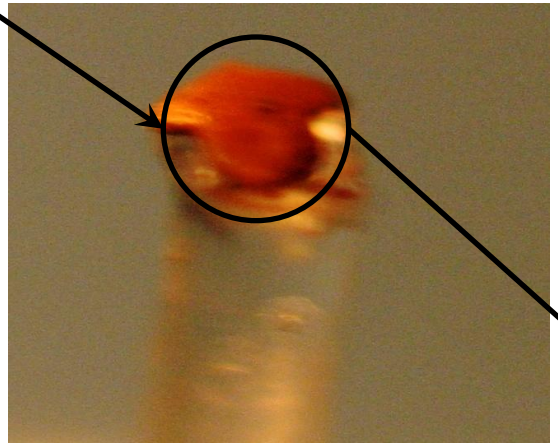
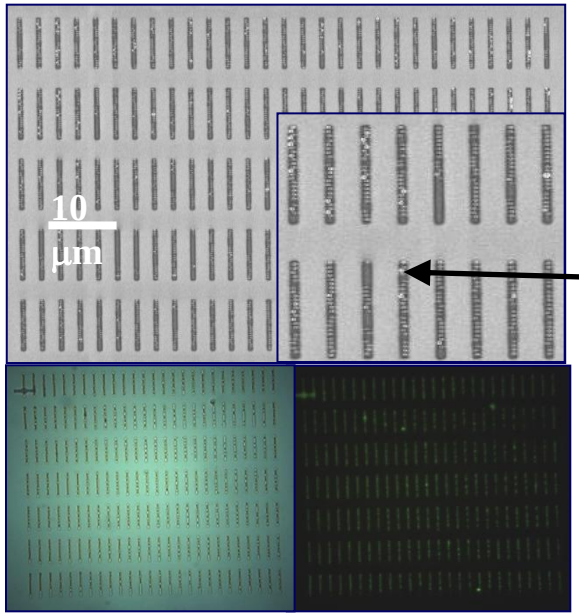
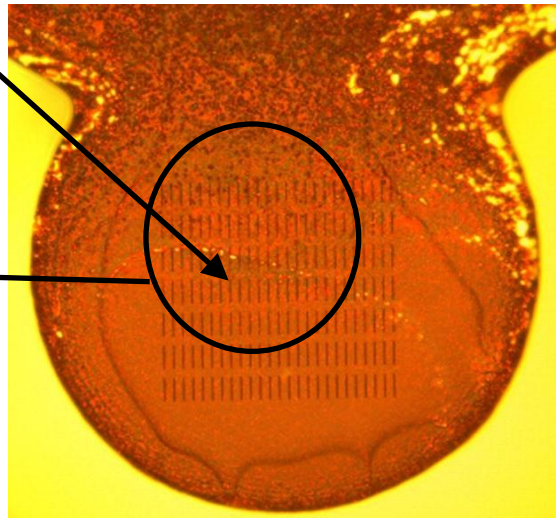



**Image of the *in-vivo* biosensor (0.1 mm x 0.1 mm) after animal testing**



**Langmuir, 27, 2011**
**Lab on a Chip Journal, 2012**



**Incubated with human plasma spiked with CEA**
**Detection limit: 15 pg/ml**
**Current technology detection limit is 3000 pg/ml**

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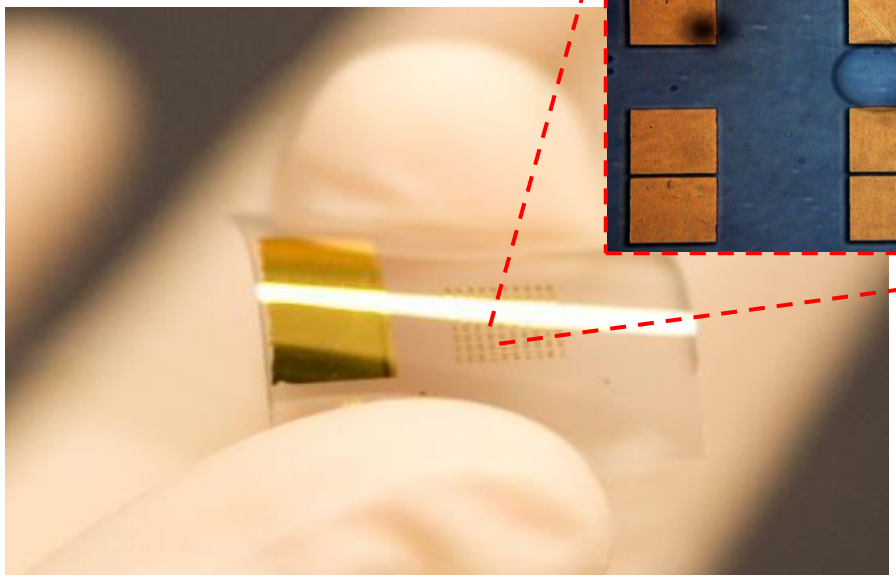
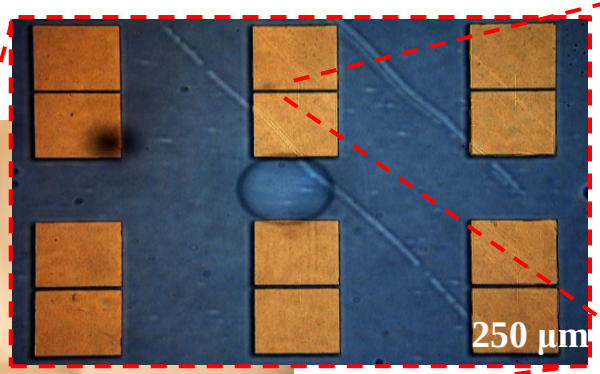
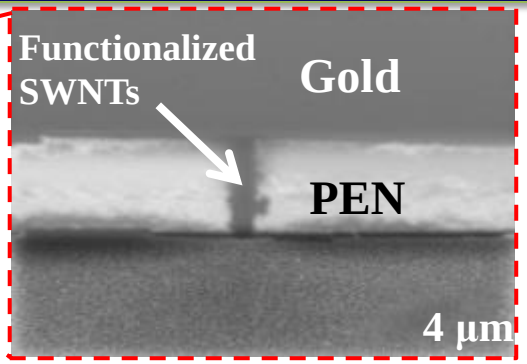
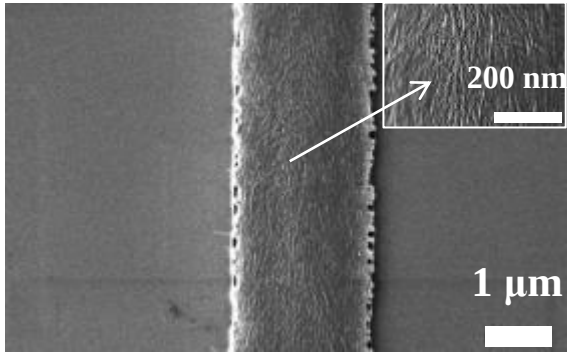
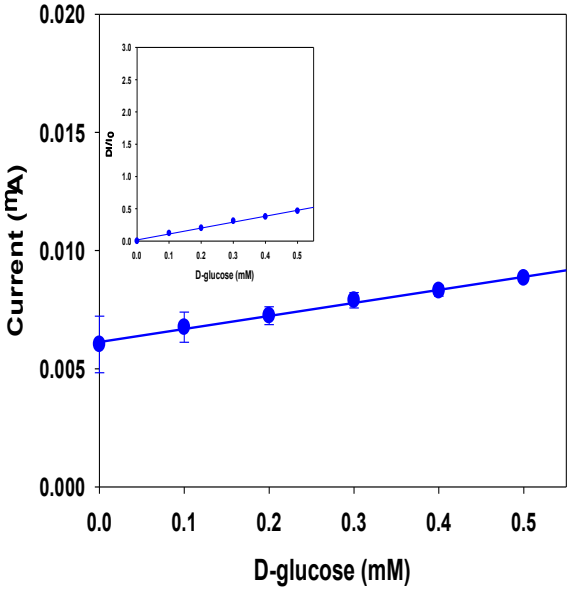
# Flexible CNT Bio sensors for Glucose, Urea and Lactate

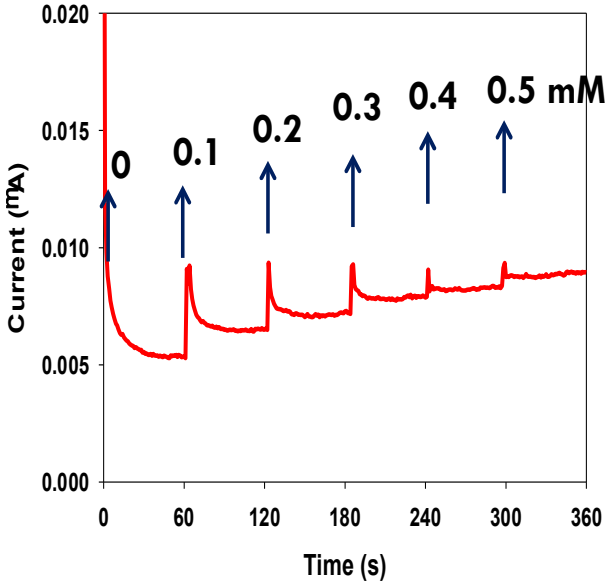


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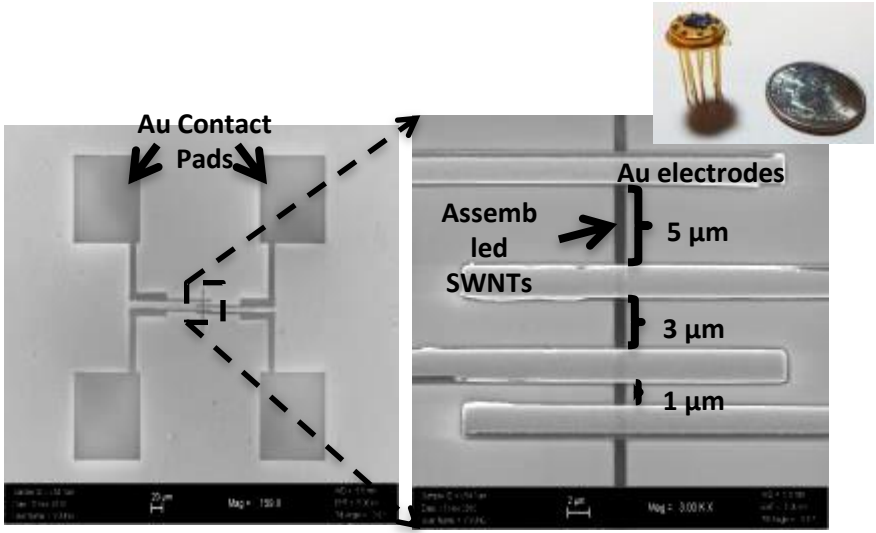
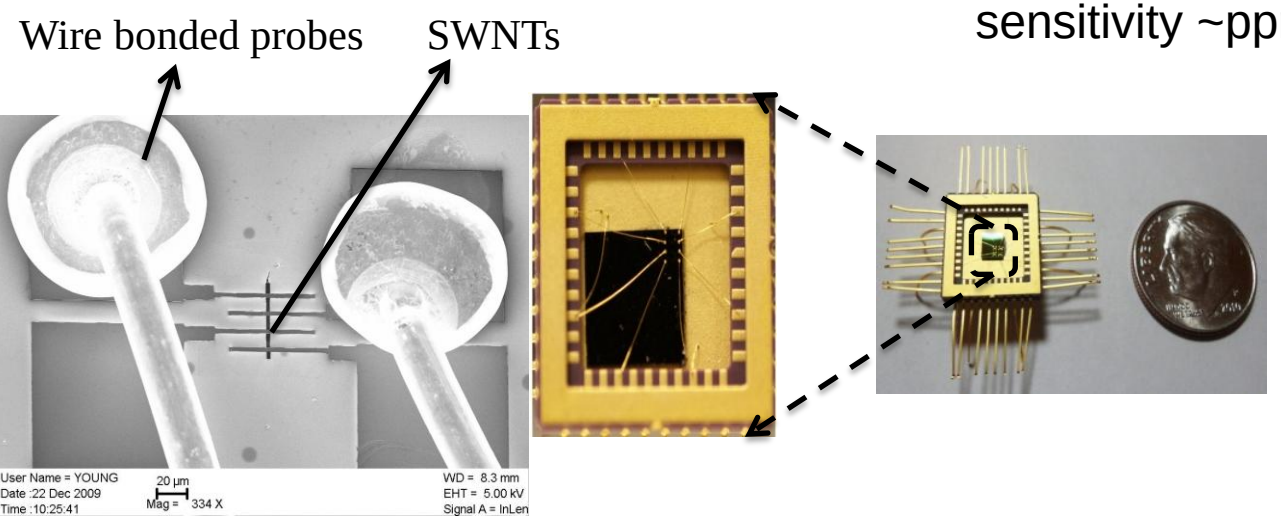
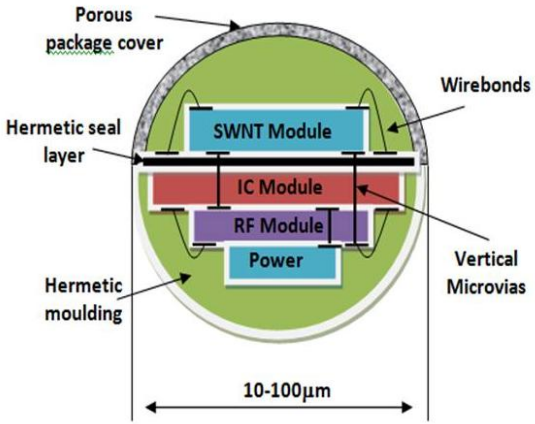
# Chemical Sensors

## Functionalized SWNT Chemical sensor




- Developed, fabricated and tested a micro-scale robust semiconducting SWNT based sensor for the detection of $H_2S$, simple alkanes, thiole, etc.
- Working in harsh environment (200$^{o}$C; 2500Psi).
- Specific in various environments ($N_2$, Air, Water vapor, Water, alkanes, etc.)
- Resistance based operation
- Simple inexpensive 2-terminal device High sensitivity ~ppm.

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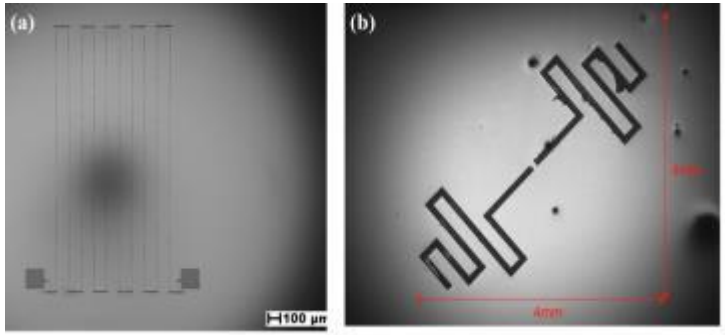
# Energy Harvesting

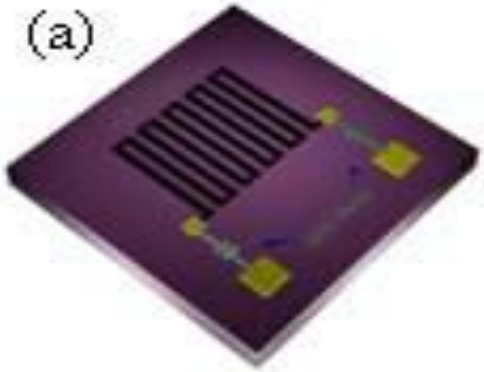
# Energy Harvesting

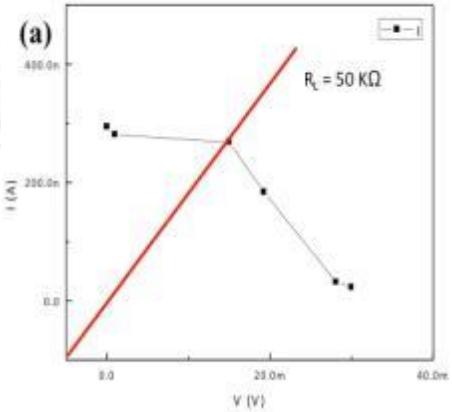
## SWNT based infrared energy harvesting device

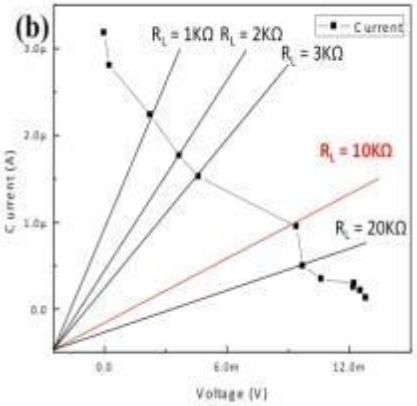



- Developed rectifying SWNT antennas having the potential for absorption of far and mid-Infra red incident light.
- Developed both Zig-Zag and linear designs.
- Rectifying circuit consists of commercially available MIM diodes operating in the W band.
- Harvesting energy wherever there is temperature difference of ~5 degrees

## CNT Infrared Energy Harvester

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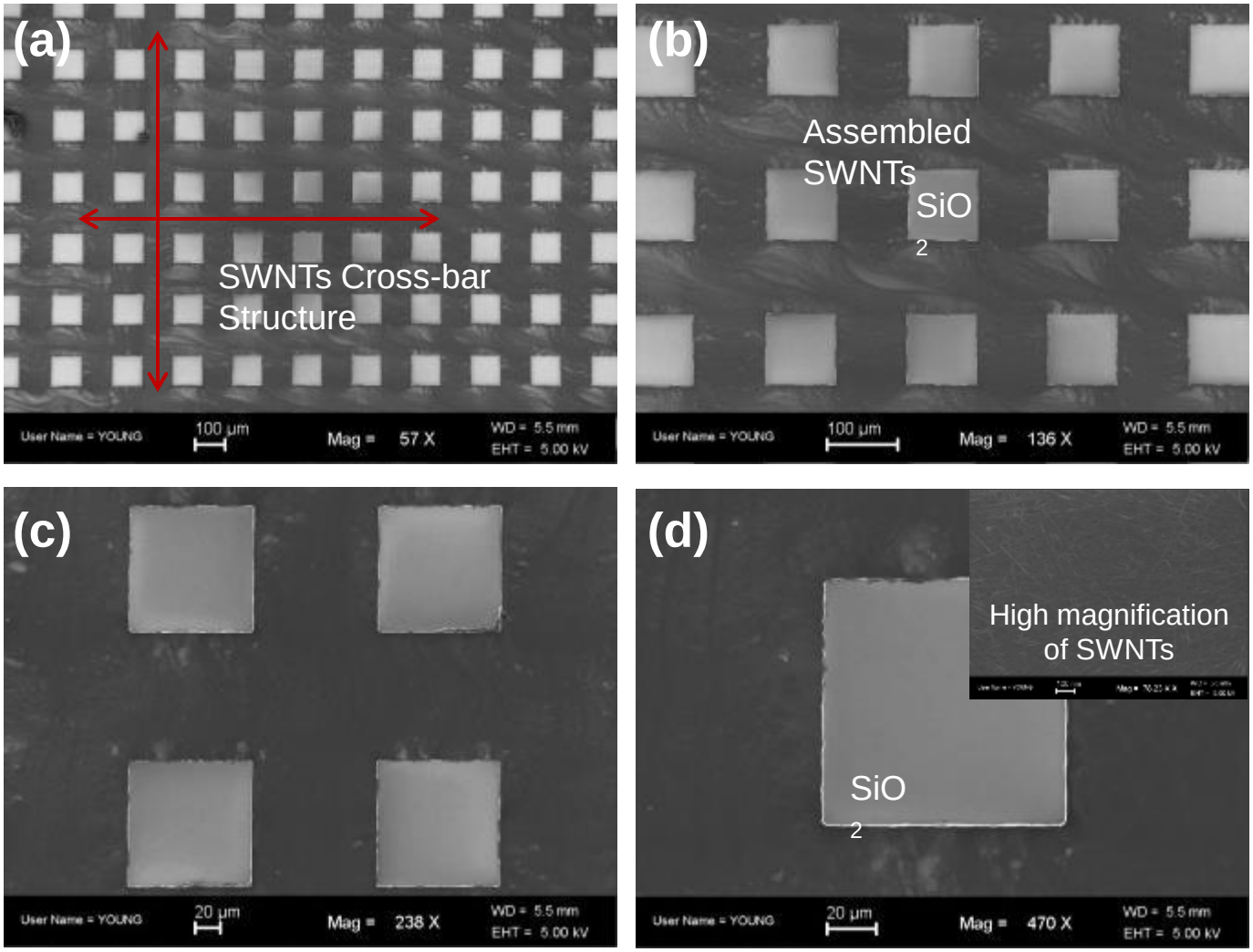
# Multifunctional Structures

# Lightweight Structural Materials for Shielding and Composite Multifunctional Structures

- ***SEM Images of Cross-bar Structure***

**Patterned and aligned carbon nanotubes**

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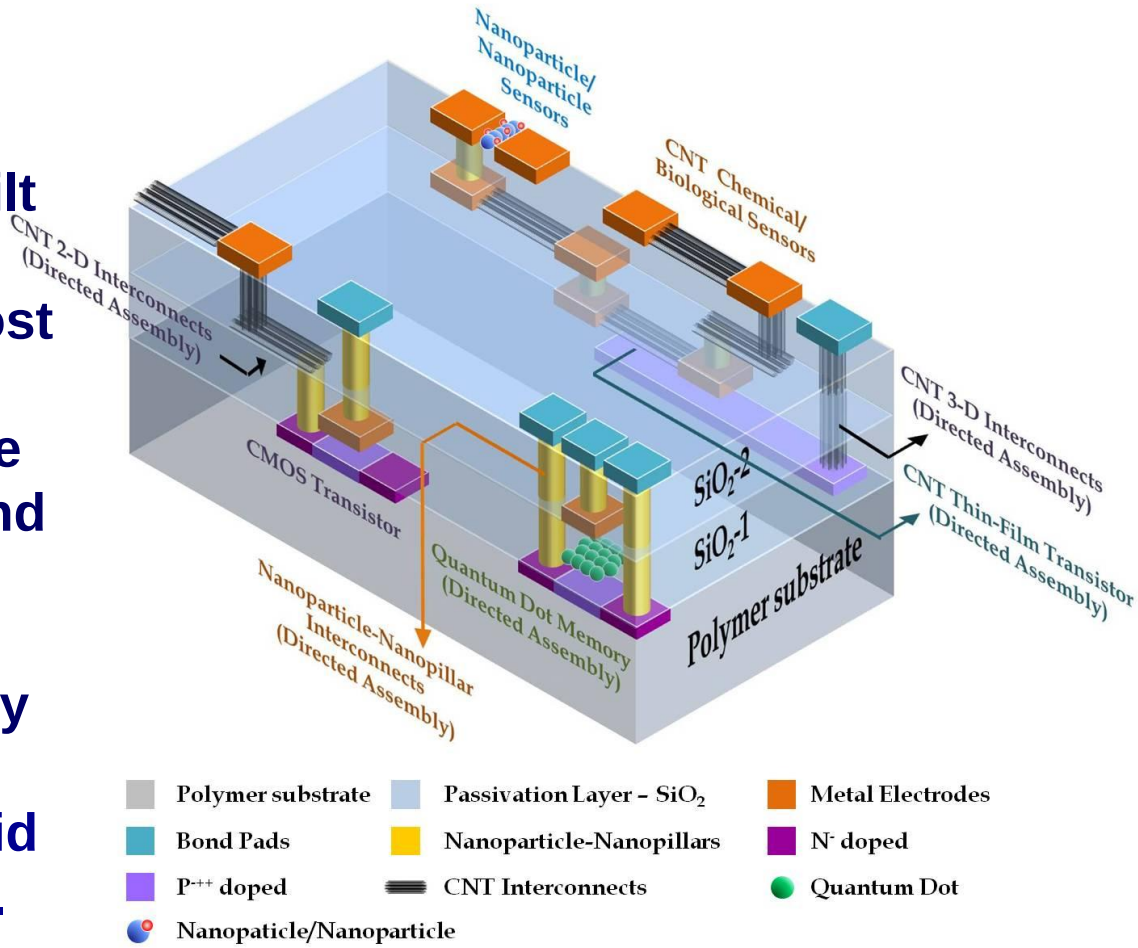
# Where do we go from here?

# Enabling from Nano to Macro; from Electronics to Medicine; from Energy to Materials

- This technology is a great enabler and equalizer
- A nanofactory could be built for under $50 million, a small fraction of today's cost
- Nanotechnology accessible to millions of innovators and entrepreneurs
- Unleash a wave of creativity in the same way as the advent of PC technology did for the computing industry.

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# What's Next?

- How to commercialize nanomanufacturing?
- What are the application requirements? (application driven process and scalability)
- How to do we get industry interested and engaged in making products using the developed processes.

# Questions and Discussion?